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This work was supported by the Federal Panel on Energy R&D (PERD)

ENERGY BALANCE MEASUREMENT SYSTEM FOR AGROFORESTRY APPLICATION IN NEWFOUNDLAND

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NEWFOUNDLAND FORESTRY CENTRE
INFORMATION REPORT N-X-251

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ISSN NO. 0704-7657
CAT. NO. Fo46-15/251E
ISBN NO. 0-662-15158-5

Copies of this report are available at no charge from:

Newfoundland Forestry Centre
Canadian Forestry Service
Box 6028, St. John's, Newfoundland
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ABSTRACT

This report summarizes the construction, laboratory and field testing of an energy balance measurement system for studies on energy plantations in Newfoundland. The system includes (1) a Reversing Temperature Difference Measurement System (RTDMS), (2) thermopiles for the measurement of dry- and wet-bulb temperature difference, (3) a net pyrradiometer, (4) a tipping bucket rain gauge, and (5) a Campbell Scientific CR7 data system.

The development work was conducted in the Department of Geography, Queen's University, Kingston, Ontario, and the field installation and testing was done at the Newfoundland Forestry Centre, Pasadena Forest Research Nursery, in the summer of 1985.

RÉSUMÉ

Ce rapport résume les travaux de mise sur pied et d'essai, au laboratoire et sur le terrain, d'un système de mesure du bilan énergétique, conçu pour l'étude des plantations de ligniculture à des fins énergétiques à Terre-Neuve. Le système comprend: (1) undispositif de mesure des écarts de température à renversement; (2) des thermopiles, pour la mesure de l'écart entre la température du thermomètre mouillé et celle du thermomètre sec; (3) un pyrradiomètre pour le rayonnement total résultant; (4) un pluviomètre à auget basculeur; (5) un ordinateur Campbell Scientific CR7.

La conception a été faite au département de géographie de l'université Queen's, à Kingston (Ontario), et la mise en place et les essais à la pépinière forestiére expérimentale de Pasadena du Centre de foresterie de Terre-Neuve, durant l'été de 1985.

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ACKNOWLEDGEMENTS

I wish to express my gratitude to Mr. Alexander (Sandy) Robertson who was helpful during all aspects of the work. He also proved to be an excellent field guide and a great source of botanical and ecological information related to the interesting sites visited in Newfoundland. Mr. Pat Dornan proved to be an excellent field assistant at Pasadena, and Mr. Calvin French was an able field assistant in the latter stages of the field testing. Particular recognition is due Mr. Mark Publicover, Department of Geography, Queen's University, who not only built the RTDMS, but also had significant input into all stages of design and testing of the equipment. Mrs. S. McCaughey did all of the typing in exemplary fashion, and I am very grateful to her. Mr. Ross Hough, Department of Geography, Queen's University, drew the diagrams. Mr. Bruce Pond, Department of Geography, Queen's University, completed the development of the necessary software and solved the various compatibility problems with the Digital Rainbow-100 microcomputer. Funding for this contract was provided through the ENFOR Program of the Canadian Forestry Service, Newfoundland Forestry Centre.

INTRODUCTION

As discussed by Robertson (1984a; 1984b), agroforestry utilizing short-rotation willow plantations could become an important element of forestry practice in the boreal regions. Therefore, it is important to understand the interactions of such plantations with the climatic environment in a fundamental way in order to match clones and sites. There is a need to document the characteristics of radiant energy receipt and the sensible and latent heat transfers between the plantation and the soil and atmosphere.

This report describes the development and field testing of an energy balance measurement system for application in Newfoundland. The central piece of equipment is the Reversing Temperature Difference Measurement System (RTDMS) which is used to measure the Bowen ratio. In association with other supplementary measurements, the sensible heat flux and latent heat flux (evapotranspiration) are calculated. The analysis programs have been developed and interfaced with the available field data system. The software has been modified to run on the DEC Rainbow-100, the microcomputer model in use in the Newfoundland Forestry Centre.

The development phase of the work commenced October 1, 1984 and field testing in June 1985 with the installation of the equipment at the Pasadena Forest Research Nursery, Pasadena, Newfoundland. This report describes the development and field testing of the equipment and software.

THEORETICAL CONSIDERATIONS

The basic theory necessary for an understanding of the energy balance will be presented. The net radiation links both the radiation and energy balances of a surface and is a fundamental variable in the understanding of the energetics of natural surfaces. It represents the net amount of radiant energy available to the surface.

Radiation Balance

The radiation balance is written as

$$Q^* = (K\downarrow - K\uparrow) + (L\downarrow - L\uparrow), \qquad (1)$$

where Q^* is the net radiation, $K\downarrow$ is the global solar radiation, $K\uparrow$ is the reflected solar radiation, $L\downarrow$ is the downward atmospheric radiation, and $L\uparrow$ is the upward terrestrial radiation. All the terms are measured in W m^{-2} for hourly averages, and period totals are given in either MJ m^{-2} or kJ m^{-2}. $K\downarrow$ and $K\uparrow$ are the shortwave terms with a spectral range across the solar spectrum from 0.1 to 3.0 μm, and $L\downarrow$ and $L\uparrow$ are the longwave or terrestrial terms which have a spectral

range from 3.0 to 100 μm. The incoming terms ($K\downarrow$ and $L\downarrow$) are controlled by the characteristics of the atmosphere, including cloud amount and type, particulate loadings (scattering ability), temperature, and the absorbing and emitting ability of the atmospheric constituents. The outgoing terms ($K\uparrow$ and $L\uparrow$) are a function of surface type and surface condition, especially the surface wetness.

The ability of the surface to modify the radiation fluxes can be shown more explicitly by the expansion of equation (1) as

$$Q^* = K\downarrow (1 - \alpha) + L\downarrow - [\varepsilon\sigma Ts^4 + (1 - \varepsilon)L\downarrow], \qquad (2)$$

where α is the reflection coefficient ($K\uparrow/K\downarrow$), ε is the surface emissivity, σ is the Stephan-Boltzmann constant, and Ts is surface temperature. α and ε are dimensionless, σ is 56.7×10^{-9} W m^{-2} K^{-4}, and Ts is measured in degrees Kelvin. It is clear that net radiation is a complex term which represents number of interactions between the atmosphere and the surface. The key surface-dependent terms in equation (2) are α and Ts. The measurement of α is achieved by two pyranometers, one facing up and the other down. Ts can be measured successfully by a non-contact infrared thermometer, or it can be estimated. If the surface is a blackbody, then $\varepsilon = 1.0$, and

$$L\uparrow = \sigma Ts^4, \qquad (3)$$

and

$$Ts = (L\uparrow/\sigma)^{\frac{1}{4}}. \qquad (4)$$

However, natural surfaces are never perfect blackbodies; rather, their emissivities are <1.0, and they are termed greybodies. For a greybody, equation (3) becomes

$$L\uparrow = \varepsilon\sigma Ts^4 + (1 - \varepsilon)L\downarrow, \qquad (5)$$

where the second term on the right is the reflected longwave component. From equation (5), Ts is

$$Ts = \left[\frac{L\uparrow - L\downarrow + \varepsilon L\downarrow}{\varepsilon\sigma}\right]^{\frac{1}{4}} \qquad (6)$$

To solve for Ts requires measurements of $L\downarrow$ and $L\uparrow$, plus an estimate of ε. The latter is usually found from the literature, and typical values for coniferous forest are 0.97 to 0.99 (Oke 1978; Monteith 1973), and 0.94 to 0.96 for deciduous leaves (Rauner 1976).

In the analysis program for the radiation balance used in this study (see Analysis Software section), equation (6) is used to calculate Ts. The value of ε is variable within the program. Also, α is calculated if measurements of $K\downarrow$ and $K\uparrow$ exist.

Energy Balance

The energy balance summarizes how net radiation is used by various processes, and it is written as

$$Q^* = Qe + Qh + Qg + Qs + Qp, \tag{7}$$

where Qe is the latent heat flux density, Qh is the sensible heat flux density, Qg is the surface soil heat flux density, Qs is the net energy storage in the biomass, and Qp is the net energy storage due to photosynthesis. For vegetation-covered surfaces, the components are ranked in approximate order of magnitude. The energy consumed by net photosynthesis is negligible in comparison to Q^*, and can be ignored in energy balance studies.

Qs is made up of three separate terms, and

$$Qs = Qa + Qw + Qv, \tag{8}$$

where Qa and Qw are the sensible and latent heat storage in the air from the ground up to the height of measurement of Q^* above the canopy (Zr), and Qv is the sensible heat storage in the vegetation. Specifically, the terms of equation (8) can be described as

$$\left.\begin{aligned} Qa &= \int_0^{Zr} \rho Cp \frac{dTd}{dt}\, dz\,, \\ Qw &= \int_0^{Zr} \frac{\rho Cp}{\gamma} \frac{de}{dt}\, dz\,, \\ Qv &= \int_0^{h} \rho veg\ Cveg \frac{dTb}{dT}\, dz\,, \end{aligned}\right\} \tag{9}$$

where ρ and ρveg are air and vegetation density (kg m^{-3} and kg m^{-3} of column), Cp and Cveg are the specific heats of air and vegetation (J kg^{-1} $°C^{-1}$), γ is the psychrometric constant (mbar $°C^{-1}$), e is vapour pressure (mbar), Td and Tb are dry-bulb air temperature and tree temperature (°C), h is canopy height (m), and t is time (s). Thom (1975) showed that equation (9) can be simplified to

$$\left.\begin{aligned} Qa &= 0.33\ Zr\ \delta Td, \\ Qw &= 0.5\ Zr\ \delta e, \\ Qv &= 0.8\ Mveg\ \delta Tb, \end{aligned}\right\} \qquad (10)$$

where Mveg is the mass of vegetation per unit horizontal area ($kg\ m^{-2}$), δTd, δTb, and δe are hourly rates of change of air and biomass temperature ($°C\ h^{-1}$) and vapour pressure ($mbar\ h^{-1}$), and 0.33, 0.5 and 0.8 the numerical constants evaluated from the combinations of ρ, ρveg, Cp, Cveg and γ from equation (9), which are assumed to be constant over the depth of canopy and the air layer up to Zr. Also, for Qv it is assumed that the specific heat of vegetation is 70% that for water. It is further necessary to measure δTd, δTb, and δe at sufficient points up to h or Zr so that "representative" values can be found. For air temperature and vapour pressure, this is relatively easy, but the measurement of δTb does present an especially challenging problem (McCaughey 1985).

Qg is solved from

$$Qg = Qg(z) + C(\Delta\overline{Ts}/\Delta t)z, \qquad (11)$$

where Qg(z) is the measured heat flux at depth z, C is the soil's heat capacity, and $(\Delta\overline{Ts}/\Delta t)$ is the rate of change of the mean soil temperature in the layer from the surface to depth z. Qg(z) is measured with one or more soil heat flux plates. The heat capacity of the soil is found as

$$C = CmXm + CoXo + CwXw + CaXa, \qquad (12)$$

where Xm, Xo, Xw and, Xa are the volume fractions of mineral matter, organic matter, water, and air respectively, and Cm, Co, Cw, and Ca are the corresponding heat capacities ($J\ m^{-3}\ °C^{-1}$). Since Ca is negligibly small, the last term in equation (12) can be ignored. Xm and Xo can be found from loss-on-ignition analysis on a minimum of two soil samples at a site; Xm is determined by the gravimetric method from 5 or 6 soil samples taken daily; and values of Cm and Co can be assigned (De Vries 1963).

Equation (11) reduces to

$$Qg = Qg(z) + (C/3600)\ \delta Ts\delta z, \qquad (13)$$

where δTs is the rate of change of mean soil temperature ($°C\ h^{-1}$) over depth δz from the surface to level z.

The solution for Qe and Qh is to measure Q^*, Qg and Qs as described above, and partition the available energy ($Q^* - Qg - Qs$) between Qe and Qh using the Bowen ratio/energy balance approach

(Tanner 1960). The Bowen ratio (β) is Qh/Qe and is found experimentally as

$$\beta = [(S/\gamma + 1)(\Delta Tw/\Delta Td) - 1]^{-1} , \quad (14)$$

where S is the slope of the saturation vapour pressure/temperature curve evaluated at the wet-bulb temperature (Tw), ΔTw is the potential wet-bulb temperature difference, and ΔTd is the potential dry-bulb temperature difference over the same height interval (Δz) in the boundary layer above the canopy. The solution for Qe and Qh is found by combining the energy balance equation with equation (14) and the turbulent transfer equations for Qe and Qh, which gives

$$Qe = (Q^* - Qg - Qs)/(1 + \beta), \quad (15)$$

and

$$Qh = (Q^* - Qg - Qs) /(1 + \beta) . \quad (16)$$

In deriving these two equations, the principle of similarity has been assumed, i.e. that the transfer coefficients for sensible and latent heat are the same for all stability conditions. Many experiments have verified this to be quite reasonable (Oke 1978).

The key difficulty in evaluating Qe and Qh is the measurement of β, and specifically, the measurement of ΔTd and ΔTw. If fixed sensors are used, it is difficult to achieve the required accuracy (Fuchs and Tanner 1970). The problem is particularly acute over rough forest canopies where, because of the intense turbulent mixing of the air, the gradients of temperature are weak. Hence, systematic errors in the measurement of temperature difference can lead to unacceptably large errors in β, Qe, and Qh. In response to this measurement problem, a number of researchers have used the approach of measuring the differences directly and interchanging the levels on a regular, short-term basis. The interchange cancels systematic errors associated with one or both psychrometers (Sargent and Tanner 1967; Gay and Fritschen 1979; Spittlehouse and Black 1980; McCaughey 1981; McCaughey and Brintnell 1984).

The RTDMS has been designed to measure the variables necessary for the calculation of β.

REVERSING TEMPERATURE DIFFERENCE MEASUREMENT SYSTEM

Construction

The RTDMS is an elevator system which interchanges the positions of the two psychrometers by slowly moving them along two adjacent rails (Figure 1). This type of interchange system has several advantages over the other commonly used system which interchanges the psychrometers in a rotary fashion around a central pivot point

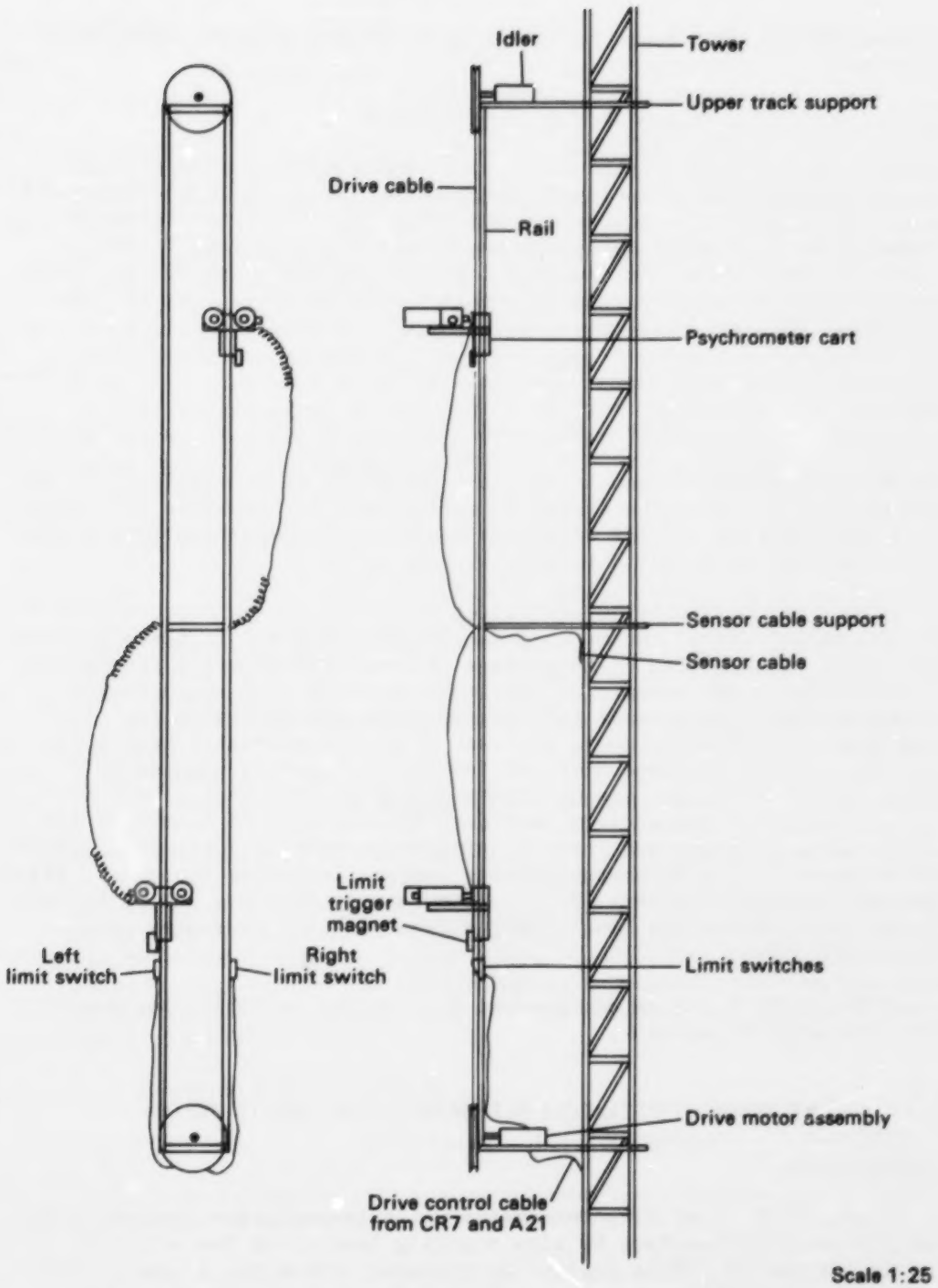


Figure 1. Schematic of Reversing Temperature Difference Measurement System mounted on a tower.

(Spittlehouse and Black 1980; McCaughey 1981; McCaughey and Brintnell 1984). The main advantages of the elevator design over the rotary design are as follows:

1. the motion is smooth and steady with no high torques placed on any part of the linkage;
2. the orientation of the psychrometers does not change during the interchange which avoids the possibility of differing radiation load on the "top" and "bottom" of the psychrometers;
3. there is no danger of over-feeding water to the wet-bulb sensors as a result of interchanging positions of the psychrometers;
4. the separation distance between the psychrometers is easily varied to accomodate sites with different boundary layer depths.

Each psychrometer is held on a horizontally oriented cart which travels along a separate vertical rail. The interchange is driven by a 12 V DC reversing motor (Globe, type EM-15, P/N 409A6217-2) which is located in a housing at the base of the rails. A drive pulley is attached to the reversing motor, and a continuous drive cable runs from it through each cart to an idler pulley attached to the upper track support positioned at the top of the rails. The tension on the cable is variable by adjustment of a small turnbuckle which connects the cable to the top of one of the carts. The other cart is held to the cable by two small screw plate clamps. Once a reversal is initiated, the motion of the carts is stopped when either one activates a limit switch positioned on the rails close to the drive motor assembly. Each switch is controlled by a limit trigger magnet which protrudes from the bottom of each of the carts. The convention of "left" and "right" is adopted in relation to the system as viewed by an observer positioned directly in front of it.

Figure 2 shows the details of a psychrometer cart. It is held on the rail by five guide wheels, and a flexible sensor support spring is attached to the back of it. The sensor cables are taped onto this spring in order to avoid their being caught between the guide wheels and the rail. At the front of each cart a mounting screw is provided for the psychrometer plate. The arrangement of the parts of a psychrometer is shown in Figure 3. The dry- and wet-bulb sensors are held inside a radiation shield which is constructed from styrofoam covered in reflective aluminized tape (Fuchs and Tanner 1965). The sensors are held in place inside a plastic tee by an acrylic plug. The other arm of the tee holds the aspiration motor. The water reservoir is positioned adjacent to the radiation shield, and water is conducted from the reservoir to the wet-bulb sensor by a cotton wick with a short piece of tygon tubing. The wick must be kept clean. It is recommended that it be washed in a mild detergent solution before installation, and that it be inspected regularly throughout the experiment. Both the reservoir and tubing are covered by reflective aluminized tape to minimize radiant heating of the water. Furthermore, a minimum of 10 cm of wick is exposed to the aspiration stream inside

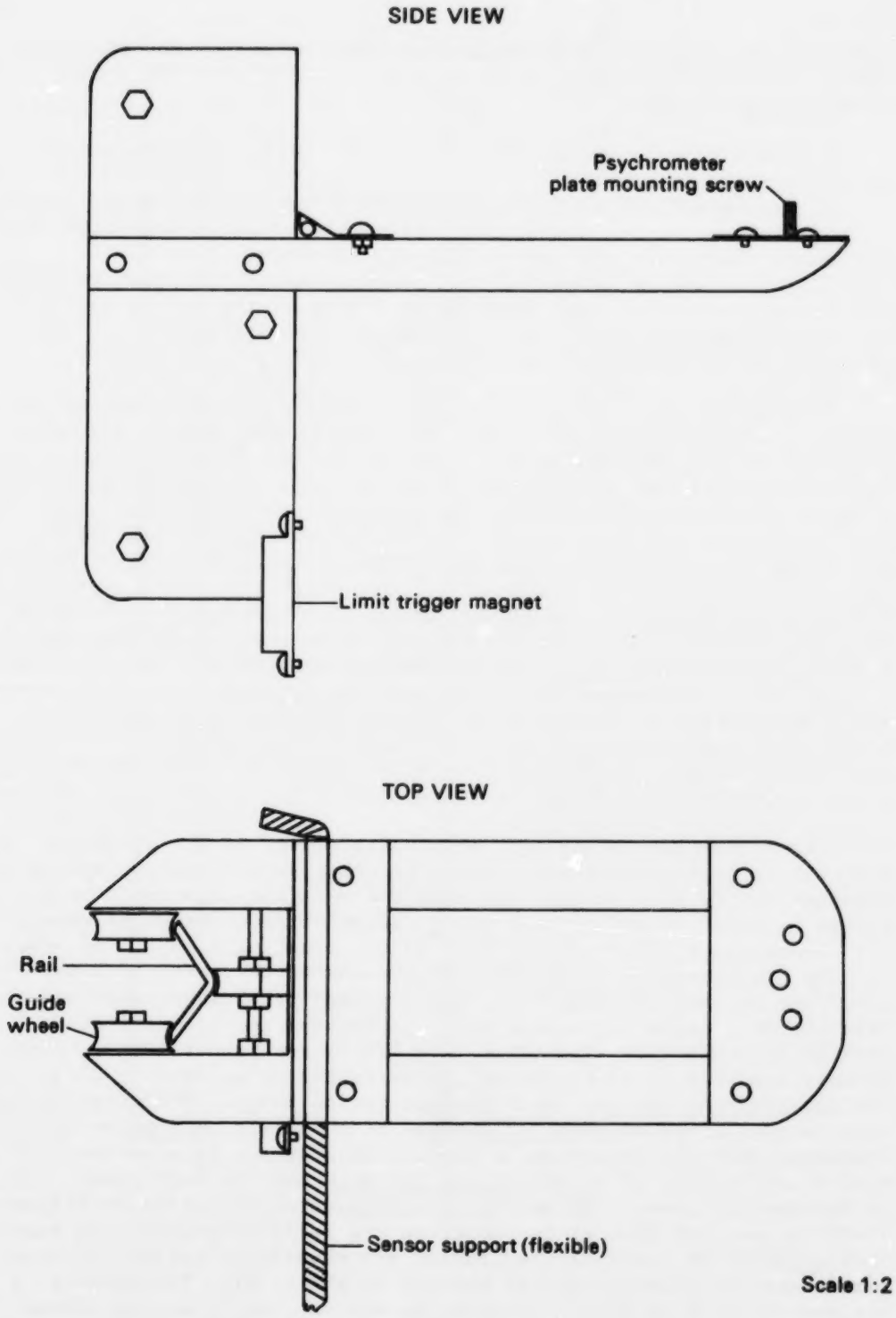


Figure 2. Psychrometer cart

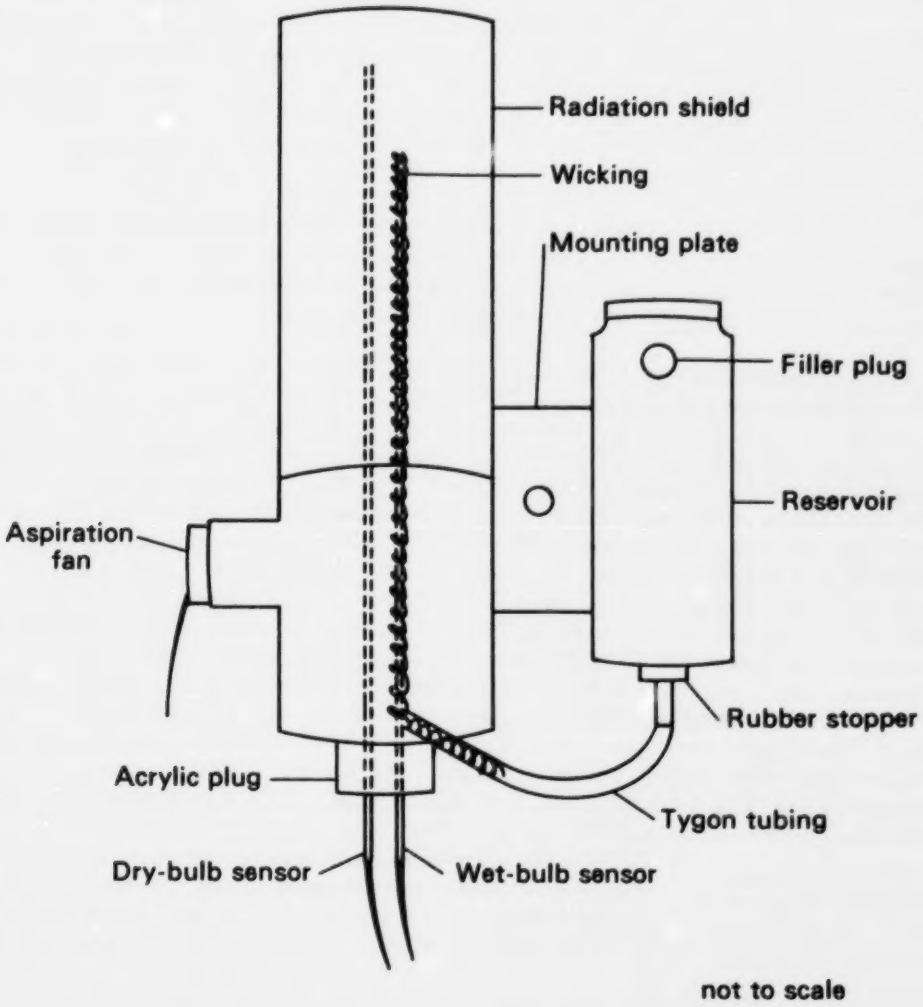


Figure 3. Schematic view of psychrometer

the shield. This ensures that the water temperature has reached the wet-bulb temperature of the air by the time it reaches the tip of the wet-bulb sensor (Lourence and Pruitt 1969). A detailed view of each of the parts of a psychrometer is shown in Figure 4. The radiation shield and fan housing are detachable to facilitate field inspection of the state of the temperature sensors. Also, the acrylic plug is detachable from the fan housing for ease of removal of the sensors in the field. Aspiration is provided by a small DC-powered fan (Micronel V361L). The aspiration rate was measured with a hot wire anemometer in the laboratory and found to be 5.4 m s^{-1} which ensures full wet-bulb depression (Tanner 1972). The anemometer was inserted through the side of the shield and positioned immediately ahead of each sensor. There was no measurable variation in aspiration rate in the vicinity of either sensor.

Figure 5 illustrates the details of the psychrometer mounting plate which attaches to the cart. The water reservoir and radiation shield are held in place by the elastic straps which hook onto the two side-mounted screws on either side of the plate.

There are three track support brackets; the upper one (Figure 6) is the same as the lower one. A middle track support, not shown in Figure 1, is used to attach two pairs of 2.5-metre-long rails together. These brackets hold the rails rigidly in place in a vertical position. The sensor cable support (Figure 7) is positioned at the mid-point of the separation distance between the psychrometer carts and may or may not correspond to the centre point of the rails. In Figure 1 they correspond and therefore, the middle track support becomes the sensor cable support. However, in order to allow for the condition where the centre point of the rails does not correspond with the centre point of the distance between the psychrometer carts, the sensor cable support must be separate from the middle track support. For example, suppose the system were mounted on a 6-metre-high tower with the lower track support at 30 cm, the middle track support at 2.8 m and the upper track support at 5.3 m. Furthermore, let us assume that the canopy is 1.0 m high, that the separation distance between the carts is 2.5 m, and that the lowest psychrometer should be at a height of 2.5 m. Thus, the sensor cable support will be at a height of 3.75 m. The only difference between the sensor cable support and the other rail support brackets is that it is not physically attached to the rails but rather, simply pressed firmly against them.

Figure 8 shows a detailed view of the drive motor assembly. The drive shaft is attached to the reversing motor and runs through two bearings to give it stability. The connection between the drive shaft and the shaft of the reversing motor is made with a 1/8" screw which passes through both shafts. This screw acts as a shear pin which will fail if the assembly jams. The wiring for the system is routed to the motor control board located immediately above the end of the reversing motor.

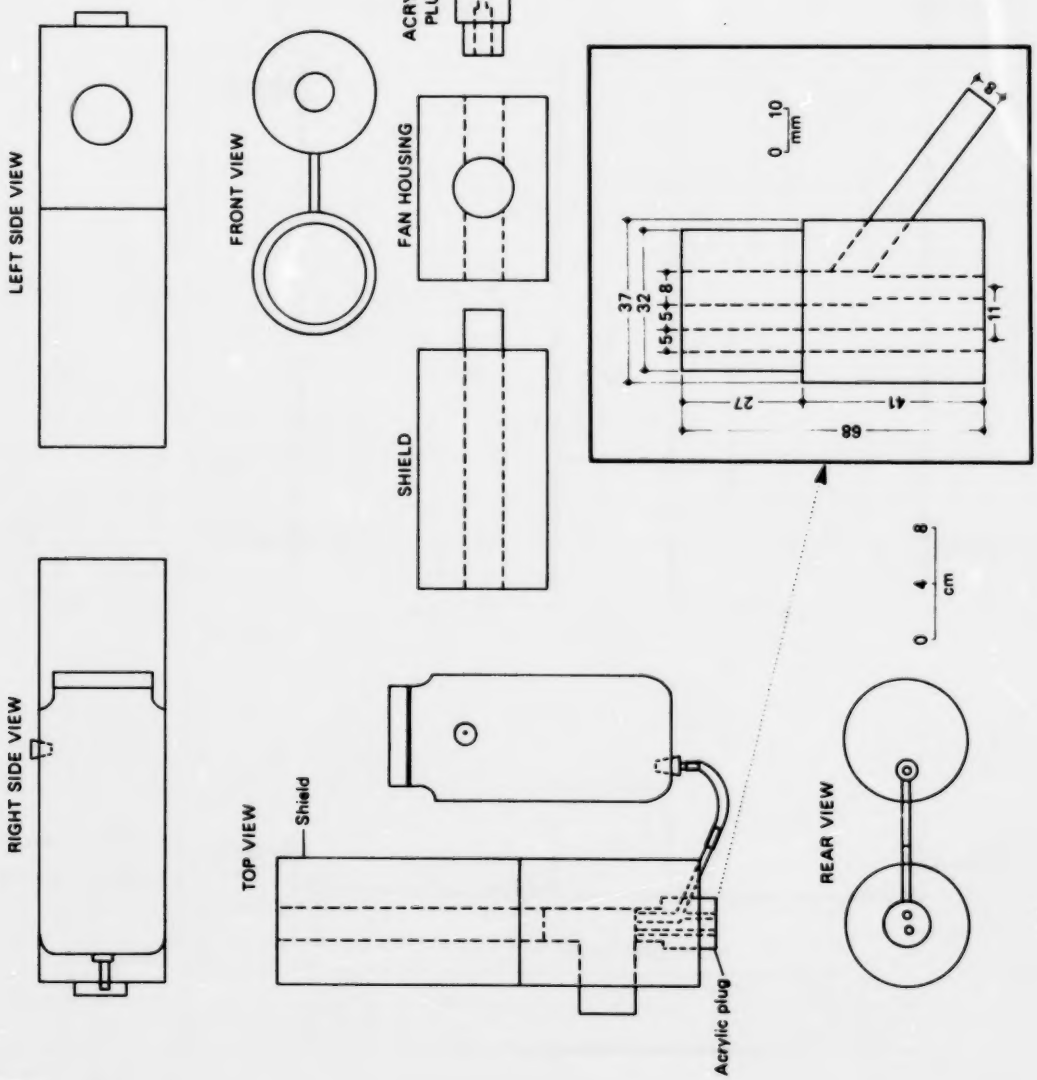


Figure 4. Psychrometer parts.

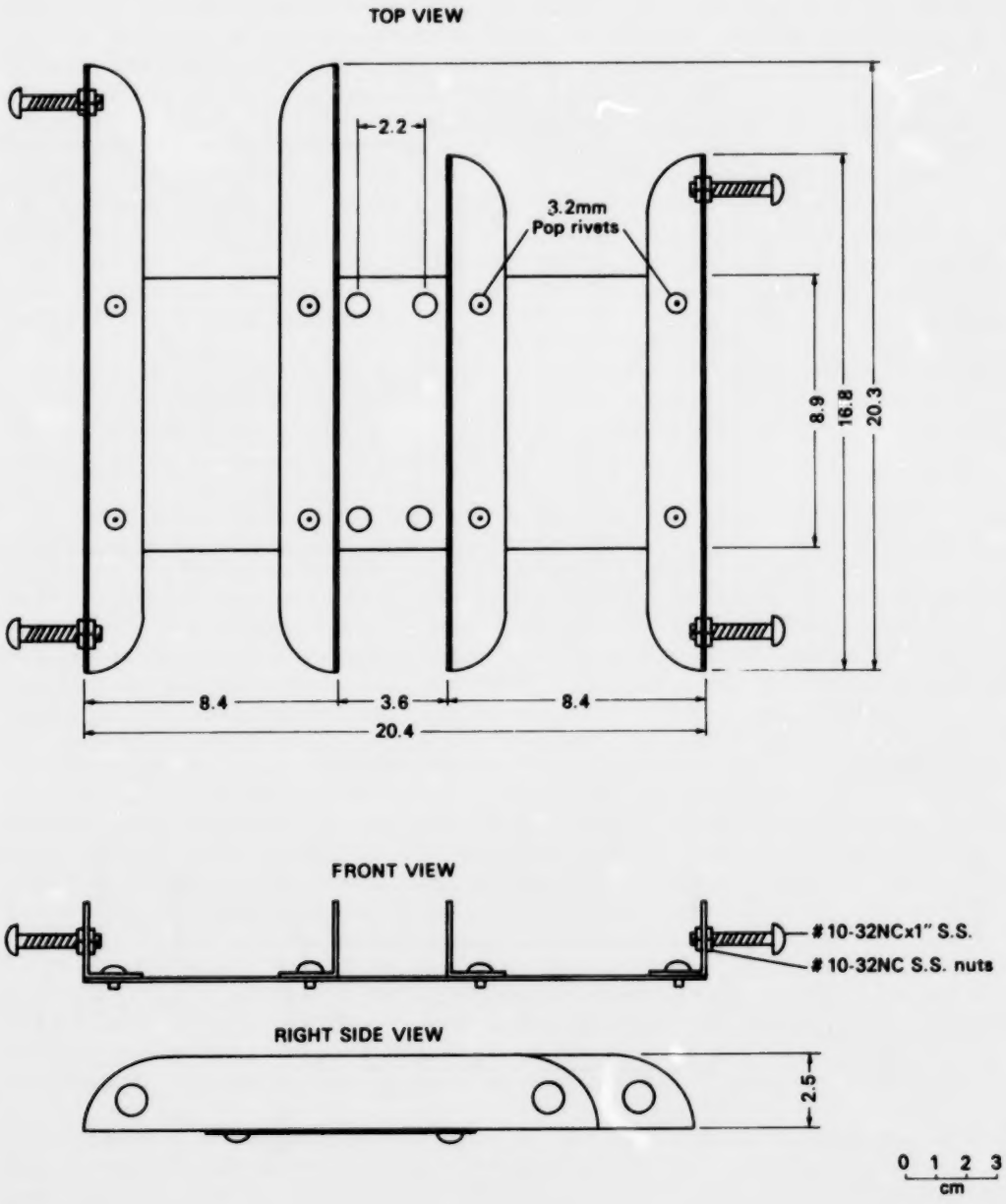


Figure 5. Psychrometer mounting plate.

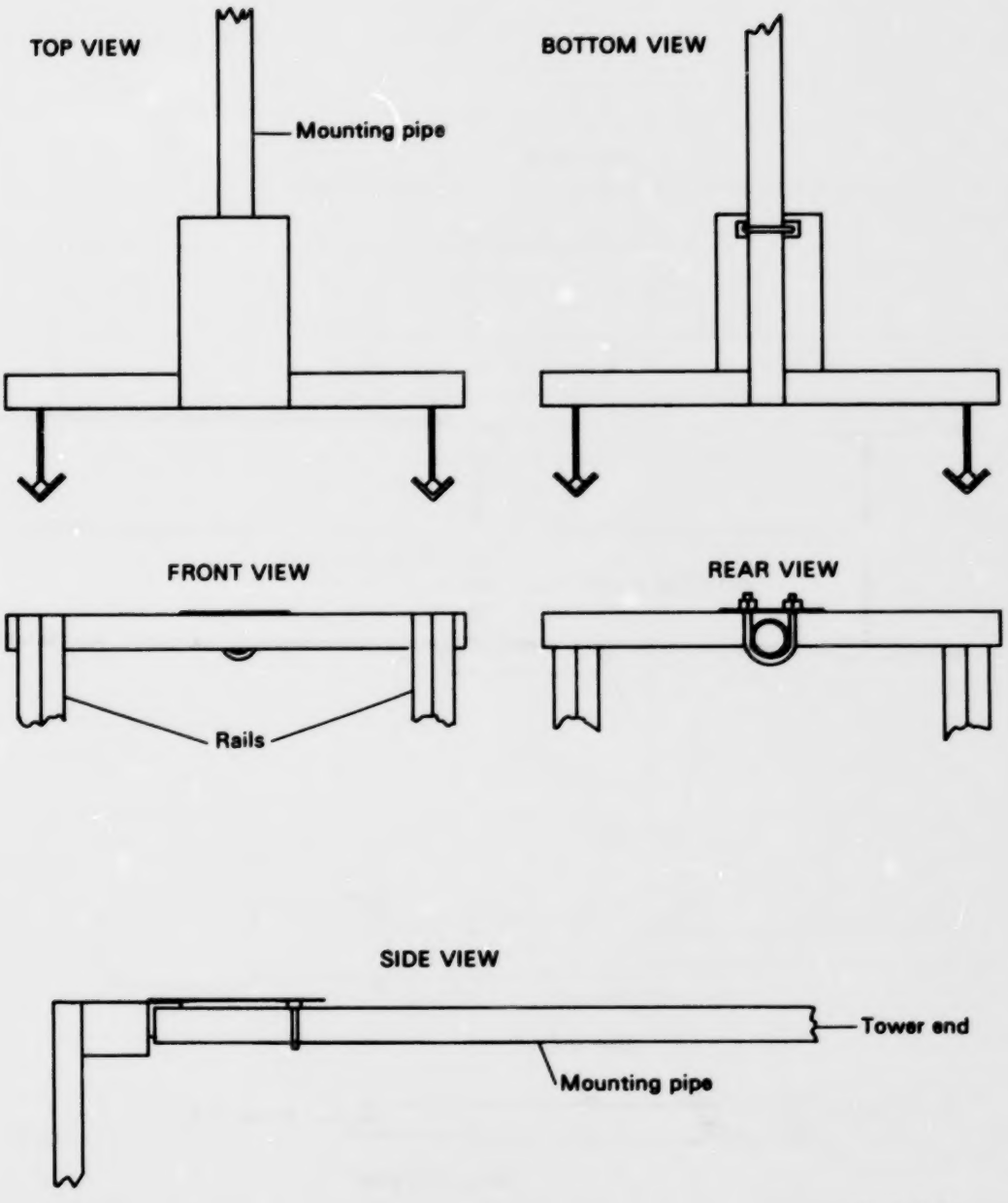


Figure 6. Upper track support.

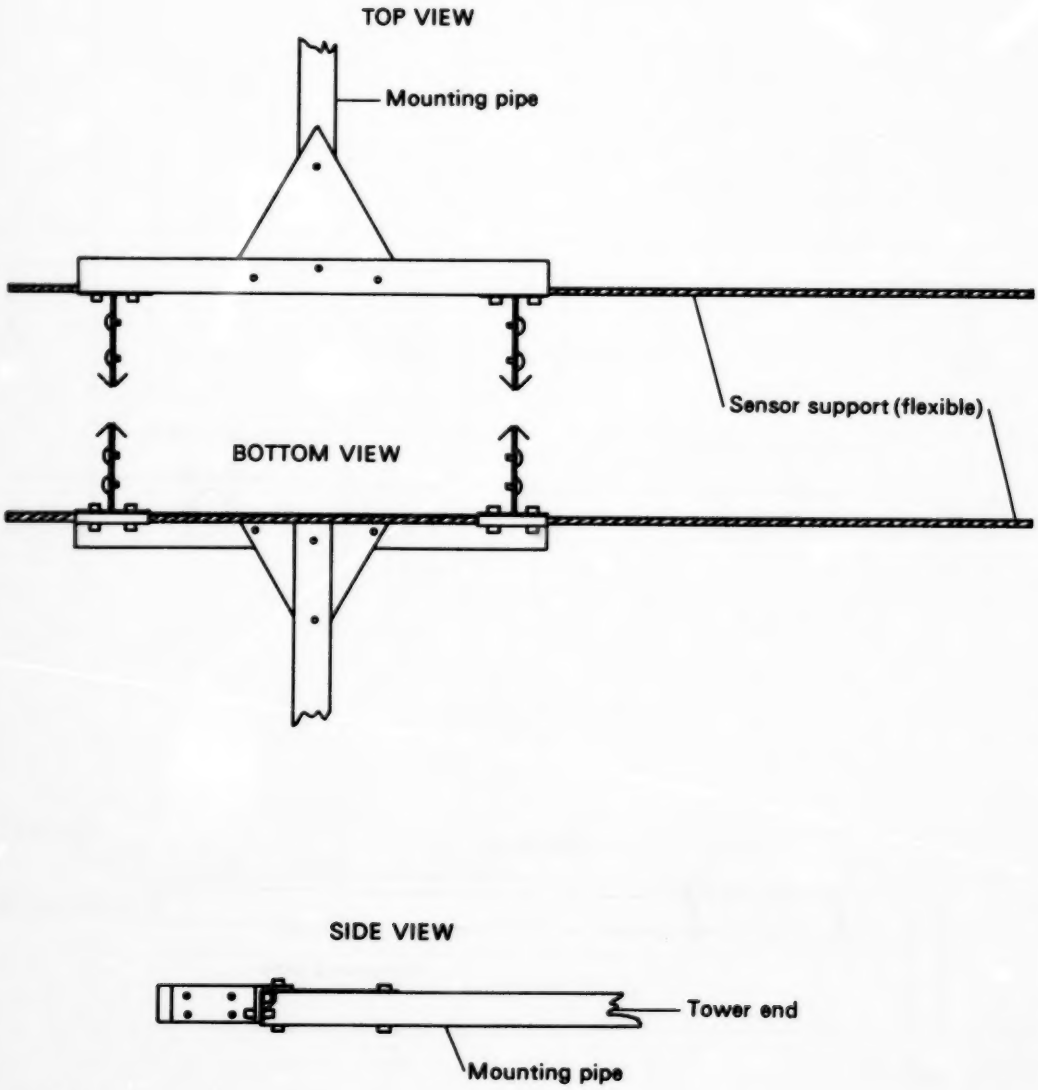


Figure 7. Sensor cable support.

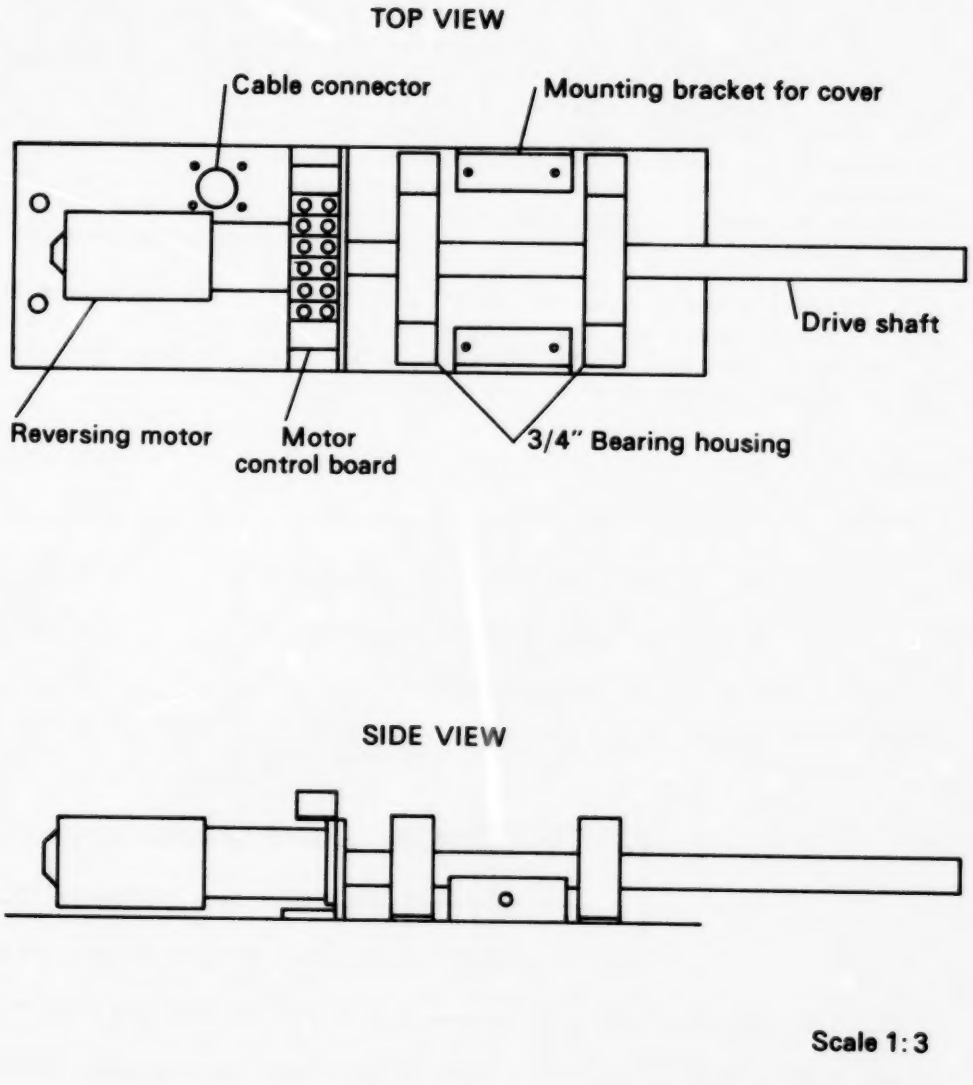


Figure 8. Drive motor assembly.

Control System

The control for initiating and stopping clockwise and counter-clockwise rotation of the reversing motor is achieved by combining the data system, (Campbell Scientific CR7), the 12 V DC relay driver (Campbell Scientific, A 21 REL), and the right and left limit switches mounted on the rails. The CR7 provides the timing for the reversals and with the digital output of a 725 excitation card, controls the operation of the relay driver. This is an improvement over earlier versions of the RTDMS, where an independent electronic timer was used to control reversals of the psychrometers (McCaughey 1981; McCaughey and Brintnell 1984). The current system keeps excellent time, and there is no possibility of the time of measurement for the various signals and the reversal time of the RTDMS becoming asynchronous.

Figures 9 and 10 show the details of the external wiring of the motor control board and the relay driver. Figure 11 shows the wiring of the left and right limit switches, and Figure 12 shows the circuit for the three relays used on the relay driver.

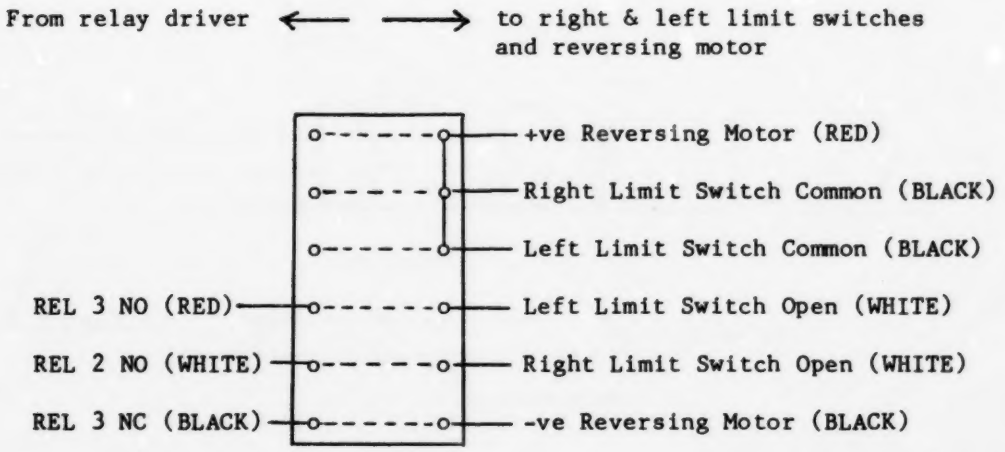
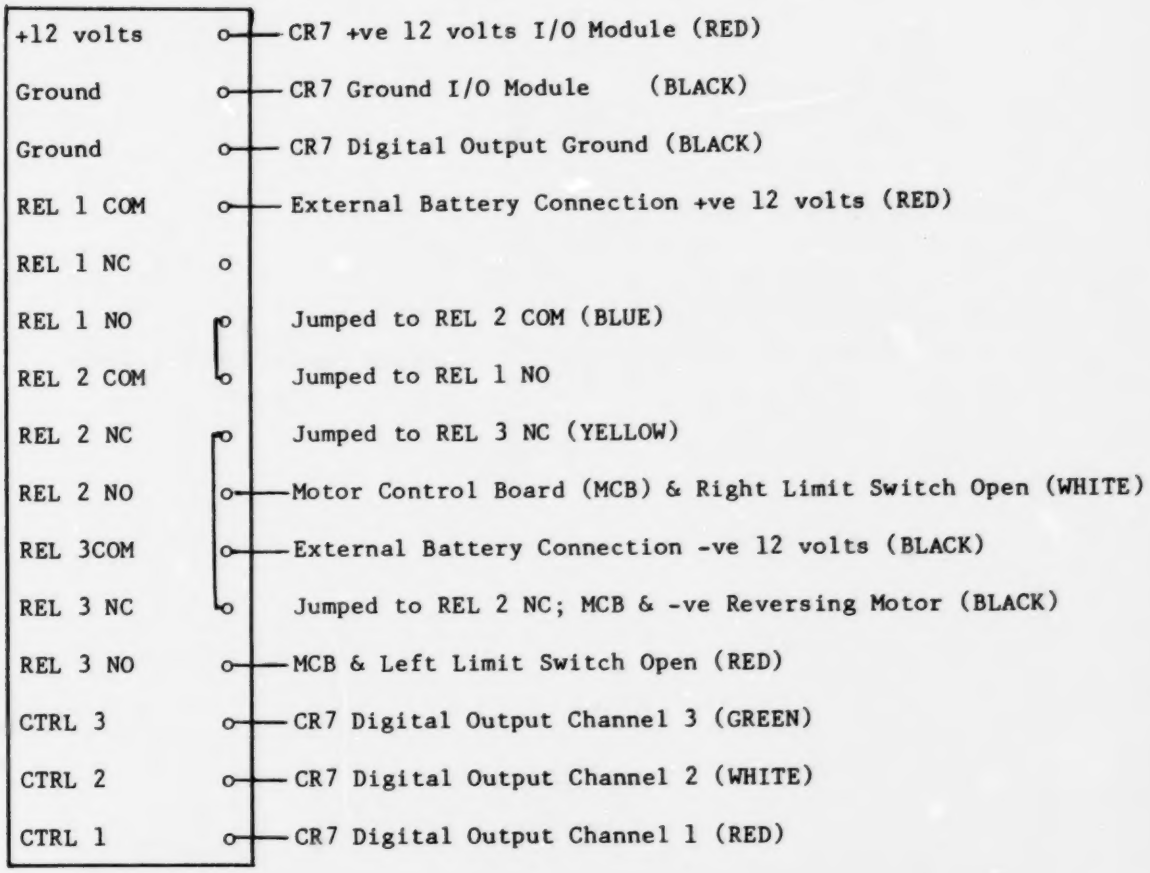

From relay driver
to right & left limit switches
and reversing motor
+ve Reversing Motor (RED)
Right Limit Switch Common (BLACK)
Left Limit Switch Common (BLACK)
REL 3 NO (RED)
Left Limit Switch Open (WHITE)
REL 2 NO (WHITE)
Right Limit Switch Open (WHITE)
REL 3 NC (BLACK)
-ve Reversing Motor (BLACK)

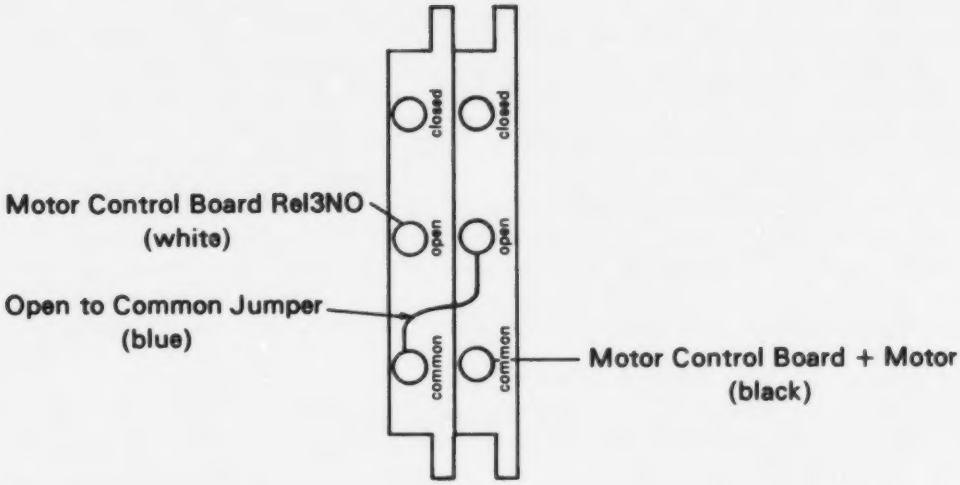
Figure 9. Wiring of motor control board.


Connected to:
+12 volts
CR7 +ve 12 volts I/O Module (RED)
Ground
CR7 Ground I/O Module (BLACK)
Ground
CR7 Digital Output Ground (BLACK)
REL 1 COM
External Battery Connection +ve 12 volts (RED)
REL 1 NC
REL 1 NO
Jumped to REL 2 COM (BLUE)
REL 2 COM
Jumped to REL 1 NO
REL 2 NC
Jumped to REL 3 NC (YELLOW)
REL 2 NO
Motor Control Board (MCB) & Right Limit Switch Open (WHITE)
REL 3COM
External Battery Connection -ve 12 volts (BLACK)
REL 3 NC
Jumped to REL 2 NC; MCB & -ve Reversing Motor (BLACK)
REL 3 NO
MCB & Left Limit Switch Open (RED)
CTRL 3
CR7 Digital Output Channel 3 (GREEN)
CTRL 2
CR7 Digital Output Channel 2 (WHITE)
CTRL 1
CR7 Digital Output Channel 1 (RED)

All connections to Relay 4 were not used and are not shown in diagram.

Figure 10. Wiring of the relay driver.

LEFT SIDE



RIGHT SIDE

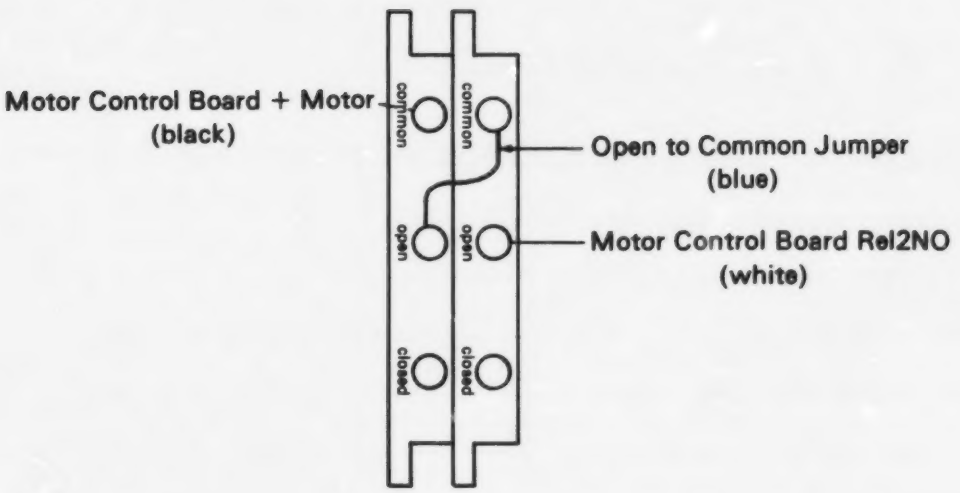


Figure 11. Left and right limit switch wiring.

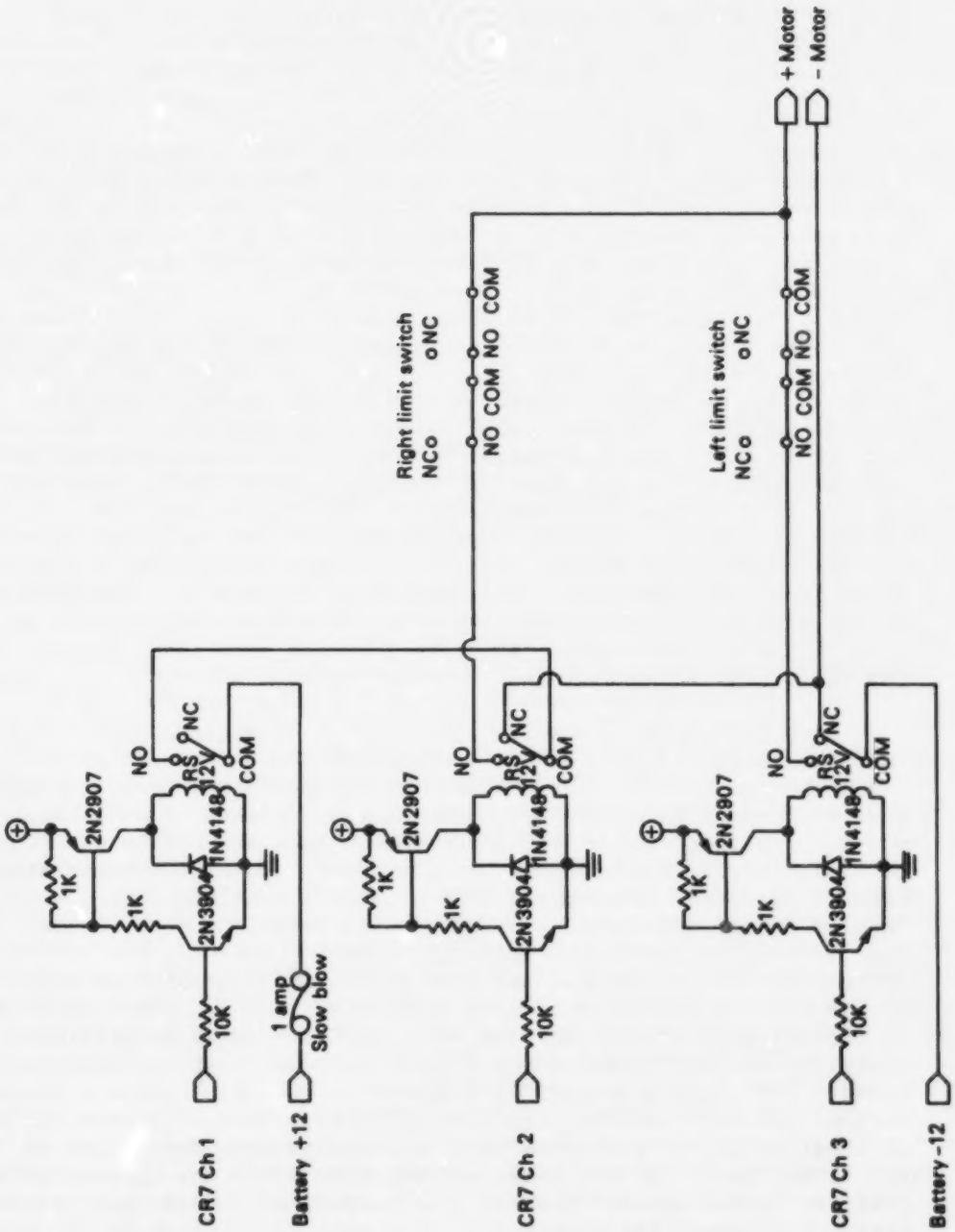


Figure 12. Relay driver circuit.

Temperature Sensor Construction and Calibration

The dry- and wet-bulb temperature differences in the RTDMS are measured with 5-junction copper-constantan thermopiles. Each thermopile is 4.3 m long, allowing for a maximum separation distance of 3.0 m between the psychrometers. The difference in these lengths, 1.3 m, allows for the lengths taken up in the psychrometer and in routing the wire across the sensor cable support. Each thermopile was made from 30 a.w.g. wire (Omega Eng. Co.), and individual thermojunctions were soldered and coated with a high thermal conductivity resin (Omegabond 101) to seal and insulate them. Each group of five thermojunctions was potted in a thin-walled aluminum tube (4.7 mm OD, and 0.15 mm wall). The tip of each tube was filled with Omegabond resin to a depth of 3 cm completely surrounding the group of thermojunctions. The use of this resin gave an acceptably low time constant of one minute. The tubes for the wet-bulb were 23 cm long, while those for the dry-bulb were 28 cm long. For each thermopile, one end was identified as the hot side, and the other labelled as the cold side. This is necessary in order to preserve consistency in the polarity of the signals in the field (see Field Installation section). In the hot side of each thermopile a single thermocouple junction was included with the five thermojunctions of the thermopile. This thermocouple is used to give an absolute temperature. The wire between the tubes was sleeved in tygon tubing, and a plastic tee at the centre point protected the connections of the positive and negative thermopile wires to a short length of two-conductor signal cable (22 a.w.g). The junctions of the aluminum tubes and the tee to the tygon tubing, and the junction of the tee and signal cable, were sealed with heat-shrinkable tubing to provide strength and waterproofing.

Each thermopile was calibrated separately using a platinum resistance thermometer (PRT) as the standard (Rosemount sensor 104 mb and linear bridge 414 L). The calibration was performed over a temperature difference range of ±5°C, with an equal number of calibration points on either side of 0°C difference. Each thermopile was found to be symmetrical. The procedure involved the use of two temperature baths. One bath, constructed from a thermos bottle enclosed within an insulated box, held pebble ice mixed with water. A water-filled test tube, placed in the pebble ice/water mixture, acted as the cold stable reference, and its temperature held within 0.1°C of zero as measured by the PRT. A refrigerated bath circulator (Neslab, RTE-5) was used as the variable hot temperature bath. It has a rated temperature stability of ±0.01°C and a temperature uniformity of ±0.01°C. Initially, the thermopile ends were placed in each bath and the temperature of the cold bath measured with the PRT. Next, a series of five calibration points were determined by varying the temperature of the hot bath. Then, the procedure was repeated after the thermopile was reversed in the baths. Finally, the temperature of the cold bath was measured to check for zero drift. For each calibration point, the temperature of the hot bath was measured with the PRT. The individual

thermocouples in each thermopile were not calibrated. The general calibration equation for copper-constantan thermocouples contained in the CR7 data system was considered sufficient.

The calibration equations for the dry- and wet-bulb thermopiles were found from regression analysis, and the root mean square error (RMSE) was used as a measure of accuracy. One example of a calibration equation is

$$\Delta T = -0.02238 + 0.00497 \cdot \text{output } (\mu V)$$
$$r^2 = 0.999, \text{ RMSE} = 0.007\ (^\circ C), \qquad (17)$$

where r^2 is the coefficient of determination.

Field Installation and Testing

In June 1985, the RTDMS was set up as a demonstration at the Pasadena Forest Research Nursery, Pasadena, Newfoundland. The site was level and had recently been seeded to grass. A standard TV tower, 9.1 m high, was erected, and the bottom of the RTDMS was fixed at 30 cm. The top of the RTDMS was at a height of 5.3 m. The separation distance between the psychrometers was fixed at 2.5 m, with the lower psychrometer at 1 m. A net pyrradiometer (Middleton, model CN-1) was positioned at a height of 1.5 m and was continuously purged with nitrogen. A tipping bucket raingauge (Sierra, model RG 2501) was placed on the ground close to the tower. All signal cables were led back to a field shelter via a flexible hose buried to a shallow depth of 10 cm; this protected all signal cables from abrasion.

The hot side psychrometer was wrapped with a band of fluorescent tape around the radiation shield on the left side rail. To preserve the accepted sign convention of negative temperature differences during lapse conditions, it is essential that the hot side of the thermopile be positioned in the up position at the start of a measurement period. For example, if one assumes a lapse atmosphere with a temperature difference of -0.2°C between the psychrometers and a reversal frequency of once every thirty minutes, then the psychrometers sit in the hot-side-up (HSU) position from the full hour until thirty minutes past the hour. They then reverse and sit in the hot-side-down (HSD) position until the full hour. The measured temperature difference in the first half-hour ($\Delta T1$) is -0.2°C and in the second half-hour ($\Delta T2$) it is +0.2°C. To cancel systematic error, the hourly mean temperature difference ($\overline{\Delta T}$) is $(\Delta T1 - \Delta T2)/2$ = -0.2°C. This obeys the convention of negative differences in a lapse atmosphere and conversely, positive differences in a stable atmosphere. This convention carries through to the analysis of the data; thus, it is essential that it be preserved.

All signals were recorded on the CR7 data system in the field shelter, and all three program tables were used. Program table 1 contained all instructions for the measurement of sensor outputs and the storage of data. Program table 2 was used for recording the time of precipitation events, and program table 3 contained the instructions for the control of the reversals of the psychrometers. The basic strategy in the programming for reversal is that pairs of relays in the relay driver are turned on for two minutes immediately following the measurements at the full hour and the half-hour. The time period when the relays are activated is variable in increments of one minute. For the two minutes when the relays are fired, power is sent to the reversing motor to drive it in either a clockwise or counter-clockwise direction. Once travel is initiated, it continues for two minutes or until one of the psychrometer carts reaches the limit switch which is part of the circuit at that time. For this installation, the full travel of the carts took 1 minute, 20 seconds.

The variables measured were dry- and wet-bulb temperature difference (ΔTd and ΔTw respectively), panel temperature of the CR7 (Tref), two case temperatures (Tcase1 and Tcase2), soil temperatures at 1 cm depth (Ts1) and at 2.5 cm depth (Ts2), net radiation, dry- and wet-bulb temperature of the air (Td and Tw respectively), precipitation, and battery voltage. The panel temperature acts as a reference for the other absolute temperatures measured with copper-constantan thermocouples. The dry- and wet-bulb air temperatures were measured by the thermocouples potted in the hot side of the dry and wet thermopiles. The sampling frequency was once every 30 seconds. ΔTd, ΔTw, Td and Tw were averaged every 5 minutes. All other signals, except precipitation, were averaged every hour. As well, Td and Tw were averaged every hour. This ensured that they appeared in both the 5-minute and 60-minute outputs which simplified the data handling at the analysis stage. The calculation of the Bowen ratio requires 5-minute averages of Tw, whereas the calculation of heat storage requires 60-minute averages of Td and Tw. The measurement of battery voltage is recommended because the CR7's internal battery should not be allowed to drop below 11.76 V to avoid damage to the rechargeable internal battery. A good working rule is to change the external battery if the internal voltage reaches 12 V.

In the calculation of the Bowen ratio it is necessary to calculate hourly average temperature differences and wet-bulb temperature. The calculation is illustrated for ΔTd. The first 5-minute period after reversal is treated as an adjustment time. Given the fact that there are twelve samples per hour, the first and seventh are dropped from the analysis. The average temperature difference in the first half-hour (ΔTd1) is found as the simple arithmetic average of the second to sixth 5-minute averages, and the average for the second half-hour (ΔTd2) is found from the eighth to twelfth 5-minute averages. The overall hourly average ($\overline{\Delta Td}$) is (ΔTd1 - ΔTd2)/2.

Bowen ratios can be found for shorter time periods. For a half-hour average value, the RTDMS would be set to reverse every 15 minutes.

ANALYSIS SOFTWARE

The data from the experiment were stored on cassette tape in Format 1. This is the low density format available on the CR7, and 8000 data points can be stored on one side of a 60-minute cassette. The high speed - high density option, Format 2, is also available and allows 180,000 data points to be stored on one side of a 60-minute cassette. For most energy balance applications utilizing the RTDMS, Format 1 is satisfactory. However, for experiments which last for a long time, Format 2 should be considered in order to minimize cassette tape consumption.

The data are retrieved from the cassette and stored on computer using the C20 cassette interface. It is strongly recommended that the cassette recorder which has been used for recording data in the field also be used to dump the data through the C20 to a computer. If this is not done, then data contamination can occur as a result of small differences in the alignment of the recording heads of different cassette recorders. Furthermore, it is good experimental practice to dump the data fairly frequently, especially at the beginning of an experiment to allow the user to check the integrity of the signals. The accessible memory of the CR7 should be examined (the *7 mode) during every site visit to check for problems in the measurements.

Once the data are transferred to a computer, daily files should be created as input into the analysis programs: RADBAL, STORAG, and ENBAL. All are command-driven and interactive. RADBAL calculates the terms of the radiation balance equation, including the shortwave reflection coefficient and surface temperature. The data are listed as hourly averages, daytime and daily totals in the output table. Daytime is defined as the period of the day when net radiation is positive. STORAG calculates the individual hourly storage terms in the energy balance equation, as well as the overall storage, Qs, as a separate file to be used as input to ENBAL, the energy balance package. In addition to Qs, ENBAL requires five-minute averages of dry- and wet-bulb temperature difference, and hourly averages of net radiation, dry- and wet-bulb air temperature within and above the canopy. The terms of the energy balance are calculated and printed for each hour, and a daily summary table is provided. It is important to point out that in the Pasadena experiment only a small amount of data was collected, and the full capacity of all three analysis programs was not utilized. However, the programs have been written to accomodate full energy and radiation balance instrumentation and are flexible enough to analyze experimental data sets with the minimum of variables for energy balance work.

USER'S GUIDE

A detailed description of data preparation and the use of the analysis programs are contained in a user's guide (McCaughey and Pond 1985) available upon request to the Newfoundland Forestry Centre.

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